PHYSICAL IMITATIONS OF THE ACTIVITIES OF AMŒBA.

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PHYSICAL imitations of the activities of lower organisms, such as are given us by Bütschli and Rhumbler, have always taken a place among the "startling achievements" of science. They arouse a lively interest in the popular mind as well as in the minds of men who are seriously studying the problems which such activities present. Anything which promises a bridge from the inorganic to the organic, from the physical to the vital, demands attention. Almost all men have definite convictions as to the relation of these two fields, — convictions which are foundational for the whole superstructure of intellectual or religious life; anything which touches these convictions must awaken interest.

How far have the physical imitations of vital activities gone? What do they really show as to relation of physical and vital? In the present paper such physical imitations as relate to one of the lowest organisms, Amœba, will be examined with these questions in view. The greater number of the physical experiments relate directly to Amœba, attempting to imitate its behavior. The writer has recently made a thorough re-examination of the behavior of this animal, the results of which have been published elsewhere (Jennings, :04), so that opportunity is presented for a comparison between the imitations and the reality. By determining to what extent the physical imitations throw light on the behavior of Amœba, we shall perhaps have a fair measure of what has been accomplished in this way, and of the promise for the future.

What is the real purpose of the physical imitations of vital activities? Clearly, the final purpose is to show what physical factors are at work in these activities. But this end may be followed in many ways; what is the special purpose of the imitations?

In the best cases the physical imitations arise as follows: There is first a study of certain vital activities. This is followed by construction of a hypothesis as to the nature of the factors at work, — an explanation of the activities in terms of phenomena already known. The third step is to determine by experiment whether the supposed known factors can produce such activities; these factors are combined in appropriate ways and the results observed. If they bring about activities similar to those shown in the vital phenomena, then the explanation gains much in probability, and we have an "imitation" of the vital activities. What the imitation shows is then, as Rhumbler ('98, p. 108) has well said, that the factors assumed to be at work really can produce such activities as we attribute to them, — and this is a long step in advance. There still remains the question whether the factors in our imitation actually *are* those at work in the vital phenomena.

To enable us to judge intelligently on this final question we need an accurate knowledge of the phenomena to be explained and of the forces at work in the imitation, that they may be closely compared; imitations founded on external resemblance are likely to be misleading. We have indeed three factors to be compared, — the explanation as it exists in the mind of the investigator, the physical experiment, and the vital activity. In the best cases these three must agree; the explanation fits the experiment, and the experiment is essentially similar to the vital phenomenon, so that the explanation fits the latter also. But the explanation given may fit the physical experiment and not the vital activity, or it may not even fit the experiment; we shall find examples of both these cases.

In the commoner case, where the explanation given does fit the physical experiment, how are we to judge whether the vital activity is to be similarly explained? Evidently an explanation based on an imitation can at best fit the vital activity only in so far as the latter agrees with the imitation. Points in which it does not agree must be attributed to other factors, and if these points are essential ones for the explanation given, then we must conclude that the vital activity is not explicable in the way proposed. Further, we must determine whether certain conditions,

preceding or following, which the explanation requires are actually fulfilled in the vital phenomena.

Imitations of the movements and of the variations in form have been oftenest attempted. Almost without exception the imitations are based on the hypothesis that these phenomena in Amœba are due to local changes in the surface tension of a fluid mass. Among the earliest experiments of this sort were those of Gad ('78). Gad placed drops of rancid oils (oils containing fatty acids) in weak solutions of alkali; for example, cod liver oil in 0.2 to 0.5 % sodium carbonate. As a result of the reaction between the fatty acid and the alkali soap is produced. This lowers the surface tension of the drop of oil here and there; as a result the drop changes form, sending out projections having an external resemblance to the pseudopodia of Amœba. A number of figures showing the forms taken by oil drops under these conditions are given in *Verworn's General Physiology*. Gad pointed out the resemblance of these forms to those shown by Amœba, but did not carry the matter farther.

Quincke ('79, '88) pursued further the study of movements caused in the manner just described, and put forth distinctly the view that the movements of Amœba (as well as of other protoplasmic masses) are due to similar causes. Quincke found that egg albumen might take the place of the sodium carbonate in the experiments above described; soap is then formed and movements occur as when the alkali is used. He held that Amœba is covered externally by a thin lamella of oil; that albuminous soaps are formed on the inner surface of this, thus decreasing the surface tension, and that the movements and changes of form are due to these changes in surface tension.

Most celebrated of all imitations of amœboid movements are those of Bütschli ('90, '92). Bütschli mixed slightly damp, powdered potassium carbonate with old olive oil, of a certain degree of rancidity, and brought drops of the mixture into water on a slide. (Directions in Bütschli, '90.) After standing twenty-four hours the drops are washed and new water or glycerine supplied. The drops now show streaming movements, send forth projections (see Fig. 1, *b*), and move about. The external resemblance to the phenomena shown in Amœba is

very striking. The movements are caused as follows: The potassium carbonate is dissolved by the water and acts on the oil, forming soap. Thus after a time the oil drop is permeated throughout by minute globules of soapy water, forming a foam-like emulsion. At times one of these globules of soap bursts on the outside of the drop of oil; the soap then spreads over the surface of the oil, lowering its surface tension in the region affected. At once a projection is formed here, currents flow from within the drop toward the region of lowered tension, and the entire drop may move in that direction.

Bütschli held that the movements of Amœba take place in a similar manner. He considers that protoplasm has an emulsion structure similar in a general way to that of the oil drops, — though of course the constituents are not the same. At times the meshwork enclosing the globules breaks at the outer surface of the Amœba, allowing some of the enclosed fluid to spread over the surface. This lowers the surface tension, causing Amœba to move in the same manner as the drop of oil.

Bütschli is inclined to attach much significance to the fact that the oil drops which move in the way described have a foam-like emulsion structure, and to consider this as a support to his view that the similarly moving protoplasm is similarly constituted. But such movements are by no means specially characteristic of fluids having a foam-like or emulsion structure; many drops having this structure do not show the movements, while other drops which have not this structure show the movements equally well, as we shall see. The movements require only that there shall be some method of producing local changes in surface tension; this may be easily brought about without the emulsion structure.

Bernstein (:00) produced similar movements in drops of mercury. Sufficient mercury to make a drop or disk five to ten millimetres in diameter is placed in a flat-bottomed watch-glass. Over it is poured some 20% nitric acid, and thereto is added a quantity of a strong solution of potassium bichromate. The mixture acts chemically on the mercury, lowering its surface tension. The intensity of the action varies locally, so that the surface tension is decreased now here, now there. As a result

the mercury moves and changes form in a striking manner, sending out projections or becoming wholly irregular, at the same time moving from place to place.[1]

The present author (:02) has given another method of observing such movements. A mixture of three parts glycerine and one part 95 % alcohol is placed on a slide and covered with a large cover-glass, supported near its ends by glass rods. Beneath the cover-glass a drop of clove oil is introduced by means of a medicine dropper drawn to a fine point. The alcohol acts locally on the surface of the clove oil, decreasing its surface tension here and there. As a result the clove oil drop changes form, sends out projections and moves from place in a striking manner. The phenomena shown are similar to those in Bütschli's drops of oil emulsion. The experiments are much easier to perform than those of Bütschli; by varying slightly the amount of alcohol in the mixture one can always be certain of getting marked results. But the movements do not continue so long as in Bütschli's experiments.

In all these experiments the movements are due to local changes in surface tension. When such a local change is produced on the surface of a fluid drop a characteristic set of currents results. From the region of least tension surface cur-

[1] The attempts of Herrera to imitate protoplasmic movements read almost like a travesty of those of the authors above mentioned. Herrera made a "synthetic protoplasm" by mixing together certain chemicals which analysis showed to exist in the protoplasm of one of the myxomycetes. This mixture contained "pepsine, ... peptone, acetic fibrine, oleic acid, soap, sugar, extract of bile, a considerable quantity of carbonate of soda, carbonates of calcium and ammonium, lactate of calcium, phosphates of calcium and magnesium, sulphates of calcium and iron, chloride of sodium, soap" (Herrera, '98, p. 118). When this miscellaneous conglomeration of chemicals was wet with water it showed, as one may well conceive, many diffusion currents. Herrera considers these as a "faithful reproduction of the internal movements of protoplasm described by Van Tieghem." In a later contribution Herrera ('98a) gives an imitation of amœboid motion based on the theory that Amœba is moved by the bubbles of carbon dioxide which it gives off in its respiration. Mix bicarbonate of soda with printer's ink so that a product is obtained having a sirupy consistency. Place on a surface wet with a weak solution of tartaric acid. Bubbles of carbon dioxide are produced, of course causing the mass to change form and move; "the illusion of a living being is complete." It is only just to say that Herrera later gave up the idea that the movements of Amœba are caused in this manner.

rents pass in all directions, while an interior current passes toward the region of least tension. The reason for these currents may be seen by imagining that the drop is covered with a stretched India rubber membrane in place of the surface film. If this stretched membrane is weakened or cut at a certain point the remainder of the membrane will pull away from this point, simulating the surface current. At the same time fluid from within will be pressed out at the weakened point, — thus simulating the central current toward the point of least tension.

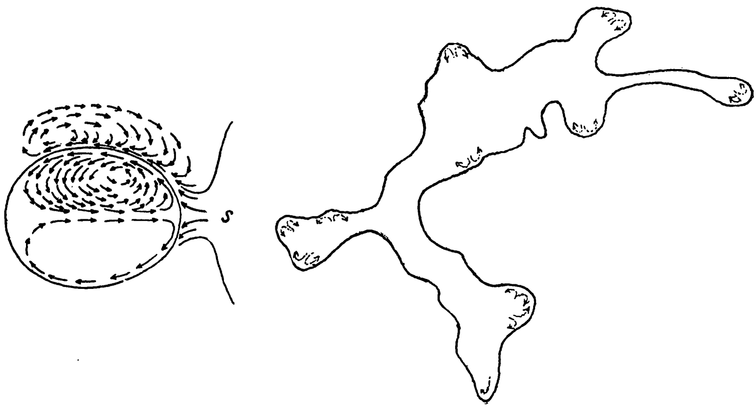

FIG. 1 *a*. FIG. 1 *b*.

FIG. 1.— Currents produced by local decrease of surface tension, after Bütschli. *a*, Currents in an oil drop when the surface tension is decreased at one end by contact with a soap solution (*s*); surface currents away from the point of lowered tension; a central current toward this point. *b*, One of the drops of oil emulsion, showing the irregular form and the characteristic currents at the tip of each projection.

The characteristic currents may be seen in Bütschli's experiments or in those with the drops of clove oil, if some soot or India ink has been mixed with the oil. Such currents are represented in Fig. 1, taken from Bütschli. If the axial current carries forward more fluid than the superficial currents carry backward, the drop may elongate in the direction of the axial current and move as a whole in the same direction. This often occurs.

Such currents as are shown in Figure 1 are an invariable feature of movements of fluids due to local decrease in surface tension. Indeed, these currents are the characteristic phenomena ; they may be the only movements that occur.

If, then, the movements of Amœba are really produced as they are in the imitations, by means of local changes in surface tension, we must expect to find in Amœba these characteristic currents. In an Amœba moving in a certain direction there should be a central current forward and superficial currents backward. In an extending pseudopodium the central current should be toward the point, the superficial currents away from it. Do such currents exist?

There is evidently a central current forward. But are the superficial currents backward, as the theory requires? In studying the movements from above, without the aid of experiment, it is difficult to determine this point. But there are certain appearances on the lower surface and at the lateral margins which give the impression that such backward currents may exist. In fact Bütschli, Rhumbler and others became convinced of the existence of such currents. The movements of Amœba were thus brought into full agreement with those of the drops moving as a result of local decrease in surface tension. This is brought out clearly by an examination of the figures of the currents in Amœba given by Bütschli and Rhumbler, copied in Figure 2. It was then almost inevitable to conclude that the same causes are at work in the two cases; that the movements of Amœba are due to local changes in surface tension.

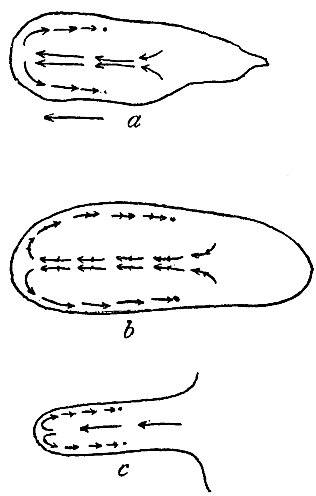

FIG. 2.—Diagram of currents in a moving Amœba, according to Bütschli and Rhumbler. *a*, Diagram of the currents as seen from above, after Rhumbler; *b*, diagram of the currents in side view, after Rhumbler; *c*, diagram of the currents in an advancing pseudopodium, after Bütschli.

In the extended experimental study of the activities of Amœba recently made by the present writer (:04), it was shown that the supposed backward currents of the surface do not exist. On the contrary, all parts of the surface which are not attached to the substratum are typically moving forward, in

the same direction as the central current, while the attached parts of the surface are at rest. The movement of Amœba is thus of a rolling character; the upper surface continually passes around the anterior end to form the lower surface; this then remains quiet until it is taken up by the posterior end as the latter moves forward. The movements in an advancing Amœba are indicated in Figure 3. In a projecting pseudopodium the movements are of the same character as those at the anterior end (Fig. 3), save when the pseudopodium projects freely into

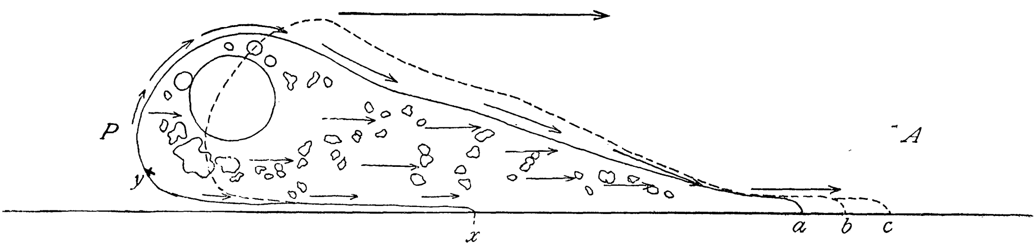

Fig. 3.—Diagram of the movements of an Amœba in locomotion, side view. The arrows show the direction of the currents; the longer arrows indicating more rapid movement. The large arrow above shows the direction of locomotion. The anterior end (A) is thin and attached to the substratum as far back as *x*; the lower surface from *a* to *x* is at rest. The posterior end (*P*) is high and rounded, and free from the substratum. *a*, *b*, *c*, successive positions occupied by the anterior end. The broken outline shows the position occupied by the Amœba a little later.

the water, being nowhere in contact with a solid. In the latter case the entire surface moves outward, in the same direction as the tip.

Details of the observations and experiments which demonstrate the movements to be of the character just set forth are given in an extensive paper published elsewhere (Jennings, :04). The movements were determined chiefly by observing the motion of objects attached to the outer surface of Amœba, of objects partly imbedded in the outer layer, and of particles within the body. The movements as thus studied are clear, and exclude the possibility of the typical existence of backward currents on the surface.

It appears then that Amœba does not move in the same manner as do the imitations based on local changes in the surface tension of a fluid mass. The currents which form the characteristic features in the latter case are not present in Amœba.

Neither theoretically nor practically does there appear to be any evidence that movements due to changes in surface tension can take place without these characteristic currents. We cannot then consider the movements of Amœba to be due to a decrease in surface tension at the anterior end, as in the "imitations." In precisely the feature which led to the supposition that the movements in the two cases were of the same character we find that there is actually an absolute contrast. In Amœba the surface currents are in the direction of movement of the mass, and in the same direction as the central current; in the imitations they are in the opposite direction.

Clearly the surface tension theory will not account for the phenomena as they actually exist. This becomes still more evident when we consider the formation of pseudopodia not in contact. In these there is not only no backward current, but also no resting surface; axis and surface move outward in the same direction as the tip. Such movements are not producible by local changes in surface tension. The "imitations" are imitations only to the extent that they are fluids and that they move; they are not imitations so far as the nature of the movements and their cause is concerned.

A much more nearly accurate imitation of the movements of Amœba may be produced with gravity as the active agent in place of surface tension. A drop of water moving down hill on a surface to which it does not cling strongly shows the same rolling movement that we find in Amœba. The lower surface (in contact with the substratum) is at rest, while the upper surface moves forward and passes continually around the anterior end to the lower surface. But we know that gravity is not the active agent in the movement of Amœba.

An imitation of the usual locomotion of Amœba that is accurate even to minute details is described by the present author in the paper on the behavior of Amœba already cited (Jennings :04). A drop of fluid resting on a substratum is caused to adhere to the substratum more strongly at one edge than at the other. Thereupon the drop moves toward the more adherent edge, and in so doing it shows exactly the form and movements of an Amœba in locomotion. The experiments may best be

performed as follows: A piece of smooth cardboard, such as the Bristol board used for drawing, is placed in the bottom of a flat dish and on a certain spot on the cardboard is placed a drop of water. The whole is then covered with bone oil. This soaks into the cardboard, except where the latter is protected by the drop of water. After the board is well soaked in oil the drop of water is removed, leaving the whole surface covered with oil some millimeters deep. Now a drop of water or glycerine, to which has been added some fine soot, is placed on the cardboard under the oil. This drop is allowed to come in contact by one edge with the area which had been protected from the oil. To this area it adheres, the edge in contact spreads out as a thin sheet, and the rest of the drop is pulled over to the area. Its movement is then exactly that typical for a flowing Amœba, so that Figure 3 would do equally well for a diagram of the movements of such a drop as for those of Amœba. The resemblance extends to minute details; many of these are set forth in the author's paper above cited (:04). Among other things, the formation of pseudopodia in contact with the substratum may be imitated by making the area to which the drop adheres at one edge very small; then a projection is formed merely of the width of this area.

But this imitation, like the others, fails when we take into consideration the formation of pseudopodia which are nowhere in contact with a solid. Projections corresponding to these cannot be formed in the physical experiments just described, for in these adherence to a solid is the essential point. Since the entire anterior end of the Amœba can be pushed out into the free water, we find that Amœba can perform all the active operations concerned in locomotion without adherence to a solid. This effectually blocks any attempt to explain the movements of Amœba as due, like those of the drops in the experiments just described, to one-sided adherence to the substratum.

Thus none of the physical imitations gives us a clue to the physical agent actually at work in the movements of Amœba. The experiments last described are perhaps useful in giving us an idea of the direction of action of the forces at work in producing locomotion. Not even so much as this can be said of

the surface tension experiments; the direction of action of the forces in these is evidently different from that in Amœba.

We may then turn to imitations of other activities of Amœba. Many attempts have been made to imitate certain of the reactions to stimuli — particularly the positive reaction to chemicals. Such imitations depend on the fact that a local decrease in the surface tension of a drop of fluid may be caused by contact with a chemical; the drop then moves in the direction of lowered tension. Some of the experiments based on this are the following:

Rhumbler ('99, p. 585) placed a small drop (60 to 90 μ in diameter) of castor oil in alcohol, and brought close to it the open end of a capillary tube containing clove oil, chloroform, or 5 % potassium hydroxide. The substance within the tube diffused out against the drop of castor oil and decreased its surface tension in the region of contact. Thereupon the usual currents were produced (Fig. 1), and the drop moved in the direction of lowered tension, finally entering the tube.

Bernstein (: 00) placed a drop of mercury in twenty per cent. nitric acid, then brought near it a crystal of potassium bichromate. By the chemical action the surface tension on the side of the drop next to the crystal is decreased. Thereupon the drop moves rapidly over to the crystal, and may push it about from place to place.

In the drops of clove oil in a mixture of glycerine and alcohol, described above (p. 8), similar movements may be caused (Jennings : 02). With a capillary pipette a little alcohol is brought near one side of the drop. This decreases the surface tension of the part affected; thereupon a projection is sent out toward the alcohol, and the drop as a whole moves toward it. If the drop is heated at one edge, by touching the cover glass near it with a hot wire, the clove oil moves toward the heated side, and may be induced to follow the wire for some distance.

In all these experiments the movement is due to local alterations in surface tension; the drop moves toward the region of lowest tension; there is a central current in the direction of locomotion, and surface currents in the opposite direction. In Amœba, on the other hand, as we have seen, the movements

cannot be considered due to local decrease in surface tension. There are no superficial currents away from the region toward which the animal moves, but all parts that are in motion move toward the object causing the reaction. (For details, see Jennings, :04.) The experiments do not imitate the essential features of the action of Amœba, and do not show us the causes at work in its behavior. The reactions of Amœba are not simple direct results of the physical action of the agents producing them, but are indirect, like those of higher animals.

Many imitations have been devised for the taking of food by Amœba. Rhumbler ('98) holds that the ingestion of food by Amœba is due to physical adhesion between the liquid protoplasm and the solid food. He shows that drops of all sorts of fluids take in certain solids in this manner. A drop of water placed at the edge of a plate of glass draws to itself and envelopes splinters of wood and various other solids which come in contact with it. Glycerine, oils, white of egg, gum arabic, mastax varnish, etc., are shown to do the same. A convenient way of showing this is to fill a capillary glass tube with the fluid, then to bring a small piece of the solid in contact with the free surface of the liquid at the end of the tube. The pulling of the solid into the liquid is due to the adhesion of the two, in connection with the surface tension of the liquid.

These experiments of Rhumbler show that food might be taken in this manner, not that it is so taken. Careful study shows that there is in most species of Amœba no adhesion between the protoplasm and the food body. Food is taken by actively enclosing it along with a small quantity of water; the fact that no adhesion exists between it and the protoplasm is strikingly evident, and occasions much difficulty in the ingestion of food. (For details, see Jennings, :04, and compare the similar account of food-taking by Le Dantec, '94.) Thus the experiments do not really imitate the essential features of the behavior in Amœba. Only in Amœba verrucosa and its close relatives is there evidence of adhesion between the animal and its food. But even here there is adhesion equally to bodies which do not serve as food and are not ingested, so that for the ingestion itself an additional factor is necessary.

One of Rhumbler's most striking experiments is an imitation of the method by which Amœba takes as food a long filament of Oscillaria, coiling it up and enclosing it. The Amœba settles down somewhere along the filament, lengthens out upon it, and bends it over, forming a loop. This process is repeated until the long filament forms a close coil within the Amœba (figures in Rhumbler, 1898, p. 211, Lang, :01, p. 39; a similar account with figure in Leidy, '79, p. 86). Rhumbler considers this remarkable process to be brought about as follows: The Amœba adheres to the filament. It lengthens out along it, just as a drop of water lengthens out along a filament to which it adheres. Owing to the surface tension of the fluid protoplasm, impelling it to take the spherical form, it pulls on the two halves of the filament, producing a thrust inward from both directions. Gradually the enclosed parts of the filament are softened in the digestive processes of the Amœba. The softened portion then yields to the thrust from both directions and bends, so that more of the filament can be pulled into the Amœba by the tension of its surface film. The Amœba then lengthens out farther, owing to adhesion; more of the filament is softened and yields farther, so that more is pulled in by surface tension. This process continues until the filament is completely coiled up and enclosed.

On the basis of this explanation Rhumbler devised an imitation of the process. A chloroform drop is placed in the bottom of a watch-glass of water. A long fine thread of shellac, obtained by heating two pieces of shellac in contact over a flame and rapidly pulling them apart, is brought in contact with the drop. The latter envelopes the filament in some portion of its length, then proceeds to coil it up, as Amœba does with the Oscillaria filament; after a time the shellac thread is completely enclosed within the chloroform drop. The mechanism of the process is conceived to be the same as that above given for Amœba and the Alga filament.

This experiment is an interesting example of one of the numerous difficulties which beset the worker along such lines, — of the fact, namely, that even the imitation may not agree with the explanation given. The coiling up of the shellac

thread by the chloroform is not explicable in the manner supposed by Rhumbler; the surface tension of the drop has really nothing to do with it. This is shown by the fact that such a thread of shellac is coiled up in exactly the same manner if submerged in a large vessel of chloroform, so that it is nowhere in contact with the surface film. The coiling up is apparently due to strains within the shellac filament, produced when it was pulled out, and to the adhesiveness of its surface when wet with chloroform. There are no corresponding factors in the Oscillaria thread; this will indeed, as Rhumbler has shown, straighten out again when released by the Amœba. The process by which Amœba coils up the Oscillaria filament must thus be of an essentially different character from that occurring in the experiment. The explanation given by Rhumbler may of course still be correct for the process in Amœba, though it is not correct for his imitation of the process.

Amœba does not ingest every small object with which it comes in contact, but exercises an evident choice as to the substances which it takes as food. Physical explanations and imitations of such choice have been given. We may notice especially those set forth by the present author (:02) in extension of certain experiments of Rhumbler. A drop of chloroform is placed in the bottom of a watch-glass of water, and with fine tweezers pieces of various substances are brought in contact with its surface. Some are at once taken in; others are not, or are thrown out if forced into the drop. Glass, sand, dirt, wood, gum Arabic, and chlorate of potash are rejected; shellac, paraffin, styrax, and hard Canada balsam are accepted. The selection or rejection depends upon the relative amount of adhesion between the solid object on the one hand and the chloroform and water on the other. Those which adhere more strongly to the chloroform than to the water are taken in; others are rejected.

These experiments show how choice might occur in an organism; they do not show how it actually occurs in Amœba. Food-taking is usually, as we have seen, not accompanied by adhesion between Amœba and the food, so that choice of food cannot be explained as due to the fact that some substances adhere while others do not.

Rhumbler ('98) has given a physical imitation of the taking in of a food body and of later giving off the undigested residue (defecation). A rod of glass covered with a thin layer of shellac is taken in by a drop of chloroform (as a result of adhesion). The shellac is dissolved off by the chloroform and the glass rod is then thrown out, since the chloroform does not adhere to it. This imitation, like the others, loses much of its force in view of the fact that food-taking is not usually due to adhesion and that substances which do not adhere are taken as food; defecation cannot then be explained as due simply to lack of adhesion.

In all the imitations thus far we find that the physical factors at work cannot be considered the same as those that are acting in Amœba. The imitations are such only in purely external features. There exist certain imitations, however, in which this has not been proved to be the case. Thus, Rhumbler ('98) found that when chloroform drops are placed in water, the water gradually passes into the chloroform, collecting in minute globules, which later gather in a larger drop. This larger drop is finally given off to the outside. This process Rhumbler considers analogous to the formation and discharge of the contractile vacuole in Amœba. The present author (:04) has described imitations of certain movements of the pseudopodia in Amœba, produced in liquids partly covered with a solid layer; these are hardly of sufficient general interest to be detailed here. The most striking experiments which can still be considered with some degree of probability to indicate the factors really at work in certain processes occurring in the Rhizopoda are undoubtedly Rhumbler's imitations of the production of Difflugia shells. Since these deal with an organism closely related to Amœba, they may be described here.

The experiments may be performed as follows: Chloroform is rubbed up with fragments of glass in a mortar until the glass is reduced to the finest dust. Then with a pipette drawn out to a small point drops of this mixture of chloroform and glass are injected into water. At once the grains of glass come to the surface of the drops so formed and arrange themselves in a single layer, without chinks or crevices, exactly as in the shell of Difflugia. The chloroform drop is thus covered with a shell

having a striking resemblance to that of Difflugia. In place of chloroform, linseed oil or other oils may be used. The drops must then be injected into 70 % alcohol, since the oil would float on water.

The factors at work in the formation of the "artificial shells" are diffusion currents within the chloroform, the adhesion of the bits of glass to its surface, and the action of surface tension in arranging and fitting together the bits of glass. Studies of the process by which the shell of Difflugia is formed at the time of division of the animal seem to indicate that the same factors may be at work in the living organism. (See Rhumbler, '98, p. 289.)

Reviewing our results, we find that few of the experimental imitations of the activities of Amœba stand before a critical comparison with what actually takes place in the animal. Such comparison shows in almost every case that the factors at work in the imitations are essentially different from those acting in Amœba. In particular, almost all the imitations based on local changes in surface tension break down completely.

What are we to conclude from this fact as to the part played by surface tension in vital phenomena? The tendency has been of late to attribute more and more of a rôle among life processes to surface tension. Amœba has been the chief place where the important part played by surface tension seemed really demonstrable; the movements, the reactions to stimuli, the taking of food, and the choice of food, were all attributed to this and closely related factors. With the demonstration of the complete failure of surface tension to account for the phenomena that were chiefly relied on to prove its importance, the supposition that it plays an immensely important rôle in life processes loses much of its weight. Surface tension may of course, in a more refined way than was supposed for Amœba, still play the large rôle in vital phenomena that some attribute to it. In the meshes of Bütschli's protoplasmic meshwork, or in the muscle fibrillæ (Bernstein), it may perhaps do what is demanded of it. Possibly the study of surface tension is still the most promising field for detection of the physical factors underlying life processes. But the surface tension theory must come to us shorn

of the trophies of its prowess, — its supposed full explanation of most of the activities of Amœba, — and bearing instead the record of a complete defeat.

What positive results of value have the physical imitations of vital activities in Amœba to show? As we have seen, there are still two or three of these that may really give us a clue to the factors at work in the vital processes; at least this has not yet been disproved. Beyond this the positive results are of a very general character. The imitations show that a drop of fluid might, through physical factors, show locomotion, move toward certain agents and away from others, and exhibit choice in the taking in of certain substances and the rejection of others. But they do not show specifically through what physical factors the activities are as a matter of fact brought about in Amœba or any other particular organism.

The chief value of most of the attempted physical imitations is that of a trial. The method of trial and error is a method of progress in science as elsewhere. In these imitations a definite explanation of the phenomena is put on trial. The "trial" consists in a more careful study of the phenomena in question; it is as an inspiration to such study that the imitations are of great value. If as a result the explanation given is recognized as "error," that is in itself an advance; this particular trial will not need to be made again. Continued application of this method of trial and error must result finally either in the discovery of the real factors at work, or in the recognition that we are dealing with a new class of factors not found in physics.

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